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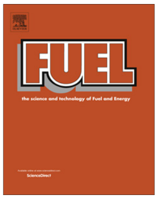

Elevating the fuel properties of *Humulus lupulus*, *Plumeria alba* and *Calophyllum inophyllum* L. through wet torrefaction

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HIGHLIGHTS

- We wet-torrefied *H. lupulus* (HL), *P. alba* (PA) and *C. inophyllum* L. (CIL) biomasses.
- The wet torrefaction efficiently elevated the fuel properties of each biomass.
- The HHVs of the solid fuels made at 260 °C are comparable to that of lignite.
- Wet torrefaction could completely destroy biomass surface.

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ABSTRACT

Wet torrefaction is an effective process to improve the fuel properties of a biomass. However, different biomasses have different component weight ratios and it is possible that not all biomasses are suitable for wet torrefaction treatment. Here we conducted wet torrefaction using three types of biomass with different component weight ratios: *Humulus lupulus* (HL, the common hop), *Plumeria alba* (PA, an evergreen shrub) and *Calophyllum inophyllum* L. (CIL, an evergreen tree). The fuel properties of the obtained solid fuels were characterized. We found that lignin made the main contribution to the solid fuel yield. The reactivity of cellulose and hemicellulose in each biomass was affected by the biomass species and the component weight ratio of the biomass. The wet torrefaction was observed to efficiently elevate the fuel properties of carbon content, atomic H/C and O/C ratios, higher heating value (HHV) and hydrophobicity of all three types of biomass. The HHVs of the solid fuels prepared at 260 °C are comparable to those of commercial coals such as Northumerland No. 81/2 Sem. Anth. Coal, Jhanjra Bonbahal Seam Coal-R-VII, and German Braunkohole lignite. These solid fuels could be co-combusted with German Braunkohole lignite without a significant change in the combustion properties of German Braunkohole lignite because of their similar atomic H/C and O/C ratios as well as HHVs. At the wet torrefaction temperature of 260 °C, the solid fuel delivered from CIL had lower HHV compared to those from HL and PA although CIL contained the highest lignin content, which has a higher HHV than those of cellulose and hemicellulose. Scanning electron microscopy images of the solid fuels revealed that wet torrefaction was able to completely destroy the biomass surface and create numerous pores and cracks on the solid fuels surface, indicating that the solid fuels have the potential to be used as a source of carbon materials such as activated carbon in addition to their use as bio-fuels.

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1. Introduction

With the increasing demand for the fossil fuels and growing concerns about the effects of carbon dioxide emissions from fossil fuels, sustainable energy sources such as biomass energy, have attracted increasing attention worldwide. Biomass energy has many advantages compared to fossil fuel: its renewable nature, relative abundance (its annual production was about eight times the total annual world fossil energy consumption), carbon neutral ability, and low sulfur emission during combustion; it is also easy to transport [1,2]. Biomasses are a promising resource for the production of liquid fuels (such as bioethanol and bio-oil), synthetic gas, hydrogen, solid fuel and valuable chemicals [3–8]. However,

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the natural drawbacks of biomass (i.e., high moisture content, hygroscopic nature, low energy density and energy value) are major barriers to the direct utilization of biomass [9]. Pretreatment of a biomass is thus needed to elevate the fuel properties (e.g., heating value, hydrophobicity, energy density) before the biomass can be used.

Wet torrefaction is considered a promising pretreatment method to improve the fuel properties of biomasses, and it has been attracted more attention in recent years. There are several reasons to use wet torrefaction as a biomass pretreatment method: (1) only water that is an environmental friendly solvent is used during wet torrefaction; (2) wet torrefaction was shown to efficiently convert biomass to bio-gases, bio-crude and solid fuel (biochar or hydrochar) [10,11]; (3) wet torrefaction is carried out at relatively lower temperature (180–260 °C) compared to dry torrefaction (approx. 290 °C), slow pyrolysis (approx. 400 °C), fast pyrolysis (approx. 500 °C) and gasification (approx. 800 °C) [12,13]; (4) wet torrefaction is more effective than dry torrefaction at the same treatment temperature to elevate the fuel properties including energy density and higher heating value (HHV), and wet torrefaction feasible for seasonal biomass feedstock [14]; and (5) it is not necessary to pre-dry the biomass, and the nitrogen oxides as well as sulfur oxides generated during wet torrefaction would be dissolved in water, making further treatment unnecessary [15].

Much information has been obtained about the wet torrefaction of biomasses. For example, Liu et al. produced solid biochar fuel with high energy density and HHV by the hydrothermal carbonization of waste biomass [16]. Chen et al. wet-torrefied sugarcane bagasse at 180 °C with different biomass-to-water ratios and treatment times in the presence of acid [7]. Yan et al. wet-torrefied loblolly pine at 200–260 °C and demonstrated that solid fuel with higher HHV and lower mass yield could be obtained at higher temperature [10,14]. Lynam et al. found that the addition of acetic acid or lithium chloride to subcritical water could increase the energy density of wet-torrefied loblolly pine [17]. However, to the best of our knowledge, there has been no report about a comparison of the fuel properties of solid fuels obtained from the wet torrefaction of biomasses with different components. The main components of common biomasses are cellulose, hemicellulose and lignin, and different biomasses have different weight ratios of these three components. This may affect the fuel properties of solid fuel obtained during wet torrefaction.

Humulus lupulus (common hop plant), *Plumeria alba* (an evergreen shrub) and *Calophyllum inophyllum* L. (an evergreen tree) are very abundant in the United States. The 2009 production of *H. lupulus* in the U.S. was 3.1×10^4 tons, and the production is expected to keep growing [18]. The mature female inflorescence or cone of *H. lupulus* is used in the brewing and pharmaceutical industries, and the leaves and stem materials have been burned or landfilled as a means of disposal [19]. *P. alba* is a 6–7-m-tall tree that is widely planted in the Hawaiian Islands. The milky sap of the stem and leaves is used in treatments for skin disease, and the extracted stem and leaves showed potential for use as an energy source although they have been disposed of as waste [20,21]. *C. inophyllum* L. (also known as Alexandrian laurel) is an evergreen tree with the average height of 8–20 m; it is widely planted in the Hawaiian Islands. *C. inophyllum* L. provides prized timber that can be used for carving, cabinetmaking and boat building [22], and its processing at timber mills produces a high amount wood flour. The remains of *C. inophyllum* L. as well as those of *H. lupulus* and *P. alba* might have potential for energy production, but it is necessary to find new ways of using their remaining biomasses. Additionally, these three biomasses have different component ratios (Table 1), and they could thus act as model materials for other biomasses with similar component ratios.

Table 1
Component contents of HL, PA and CIL biomasses.

Sample	Cellulose (%)	Hemicellulose (%)	Lignin (%)
HL	19.7 ± 2.5	36.5 ± 2.5	24.6 ± 1.3
PA	33.9 ± 4.0	22.7 ± 4.0	25.2 ± 0.9
CIL	25.2 ± 1.6	16.2 ± 1.6	38.3 ± 4.7

The values after ± are the standard deviations ($n = 3$).

For these reasons, we used *H. lupulus* (HL), *P. alba* (PA) and *C. inophyllum* L. (CIL) as raw materials for wet torrefaction in the present study. The purposes of this research were to elevate the fuel properties of solid fuels obtained from the wet torrefaction of these three types of biomass and to explore the theoretical basis for future industrial uses of wet torrefaction.

2. Materials and methods

2.1. Materials

The three types of biomass, HL, PA and CIL were produced in Guam. Their components are shown on Table 1. CIL contained the highest lignin content. HL and PA contained similar lignin content, and HL had the highest hemicellulose content. These biomasses were used without any pretreatment except milling before all of the experiments. All reagents used in this study were purchased from Wako Pure Chemical Industries (Osaka, Japan).

2.2. Wet torrefaction of the biomasses

Wet torrefaction of the biomasses was carried out in a stainless steel batch reactor (Taiatsu Technology Corp., Osaka, Japan) with the working volume of 10 mL. First, 200 mg of biomass (HL or PA or CIL) powder with 8 mL of ultrapure water was charged into the batch reactor, and the reactor was then set into a ceramic furnace (ARF-40 K, Asahi-Rika, Chiba, Japan) with a digital temperature controller (TXN-700, ASONE, Osaka, Japan). The reactor was held at the desired temperature (180–260 °C) for 10 min and then immediately immersed into an ice bath to cool down the reactor to room temperature. The mixture was then filtered through a G-4 glass filter (Vidtec, Fukuoka, Japan) to obtain the residue (which is also called solid fuel or hydrochar) [23]. The solid fuel was then dried at 105 °C until its weight reached a constant value. The solid fuels obtained at various temperatures were abbreviated as HL-xxx or PA-xxx or CIL-xxx, where HL, PA and CIL are the names of biomass and xxx is the wet torrefaction temperature.

2.3. Characterization of the biomasses and solid fuels

The lignin content was determined by a modified 72% sulfuric acid method [24]. The cellulose and hemicellulose contents were analyzed by a micro-analytical method [25]. The element contents (C, H and N) were measured by an elemental analyzer (2400II, PerkinElmer, Kanagawa, Japan). The HHVs of the biomasses and solid fuels were determined from their element contents and calculated by the following equation [26]:

$$\mathrm{HHV} = 5.22\mathrm{C}^2 - 319\mathrm{C} - 1647\mathrm{H} + 38.6\mathrm{CH} + 133\mathrm{N} + 21028 \qquad (1)$$

where C, H and N represent the carbon, hydrogen and nitrogen contents of the biomass or solid fuel, respectively, expressed in mass percentage on a dry basis. The energy yield was calculated from the HHV as well as the solid fuel mass yield by the following equation:

$$\text{Energy yield}(\%) = \mathrm{HHV}_{\text{solid fuel}}/\mathrm{HHV}_{\text{raw biomass}} \times \text{solid fuel mass yield} \qquad (2)$$

The hydrophobicity of the biomasses and solid fuels were evaluated by the following method: Approx. 100 mg of biomass or solid fuel was placed in a plastic dish and then the dish was placed in a large plastic bottle containing saturated sodium chloride solution with the relative humidity of 75%, at the experimental temperature of 30 °C. It took 15–20 days for the biomasses and solid fuels to reach equilibrium. The final moisture content was calculated by the weight difference between before and after treatment, and this value was used to estimate the hydrophobicity of each sample.

For scanning electron microscopy (SEM) measurements, the biomasses and solid fuels were sputter-coated with Pt and examined with a scanning electron microscope (S-4700, Hitachi, Tokyo, Japan).

3. Results and discussion

3.1. The solid fuel yield

The solid fuel yield reflects the thermal stability of a biomass during wet torrefaction. The yields of all solid fuels obtained from the HL, PA and CIL biomasses were examined, and the results are shown in Fig. 1. The yield decreased with the increase in the wet torrefaction temperature, indicating that temperature was an important factor that affected the solid fuel yield. Among the three types of biomass, the solid fuel yield prepared at the same temperature was in the order of CIL-xxx > PA-xxx > HL-xxx. At 260 °C, CIL produced a solid fuel yield of 50.9%, which was much higher than those of PA (31.5%) and HL (26.5%). This was due to the higher content of lignin in CIL (Table 1), because lignin has a higher decomposition temperature than cellulose and hemicellulose, and the lignin made the greatest contribution to the production of char [27]. The CIL biomass thus showed more thermal stability than the PA and HL biomasses, and higher solid fuel yield could be obtained from the biomass containing higher lignin content during the wet torrefaction process.

3.2. The components of the biomasses and solid fuels

As noted earlier, cellulose, hemicellulose and lignin are the main components of biomass. Knowing the component content in a solid fuel will help elucidate the degradation mechanism of the biomass and determine the optimum conditions for wet torrefaction. Table 2 shows the weights of the remaining cellulose, hemicellulose and lignin in the solid fuels. The cellulose and hemicellulose in the three solid fuels were significantly decomposed with the increase in the wet torrefaction temperature, whereas lignin was slightly decomposed at higher temperatures. Regarding the decomposition of cellulose and hemicellulose in the solid fuels, the weights of cellulose and hemicellulose in HL were reduced from 38.4 to 13.8 mg (64.1% decrease) and from 72.9 to 7.4 mg (89.8% decrease), respectively, with the increase of the wet torrefaction temperature. In this case, much more hemicellulose was decomposed, which was consistent with the report by Yan et al. that hemicellulose was more reactive than cellulose and could be easily hydrolyzed even at 200 °C [10]. However, our result was different from the conclusions that hemicellulose started decomposing at 200 °C and became fully devolatilized at 250 °C [28]; in another study, cellulose presented a slow decomposition rate below 250 °C and the rate became rapid above 300 °C [29].

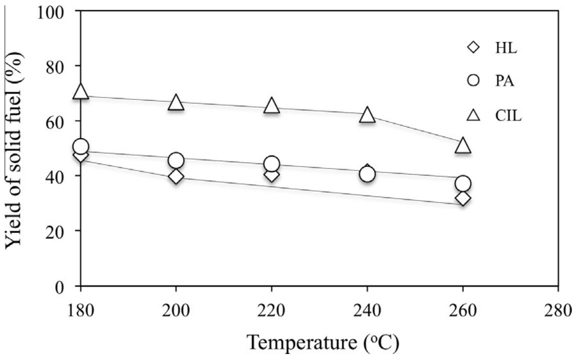

Fig. 1. Mass yield of solid fuels derived from the wet torrefaction of HL, PA and CIL at various temperatures for 10 min ($n = 3$).

Table 2
Component weights of HL, PA and CIL as well as solid fuels obtained at various temperatures for 10 min.

Sample	Cellulose (mg)	Hemicellulose (mg)	Lignin (mg)
HL	38.4 ± 4.9	72.9 ± 4.9	49.3 ± 2.6
HL-180	35.0 ± 4.7	17.8 ± 4.7	38.7 ± 1.9
HL-200	29.6 ± 0.9	15.3 ± 0.9	32.0 ± 1.0
HL-220	24.5 ± 1.0	19.5 ± 1.0	33.8 ± 0.6
HL-240	26.5 ± 0.5	11.5 ± 0.5	44.3 ± 2.0
HL-260	13.8 ± 1.1	7.4 ± 1.2	40.8 ± 1.7
PA	73.6 ± 8.0	45.4 ± 8.0	50.4 ± 1.8
PA-180	25.9 ± 0.4	20.0 ± 0.4	49.0 ± 1.3
PA-200	24.8 ± 0.5	17.0 ± 0.5	44.5 ± 0.2
PA-220	23.3 ± 4.7	15.9 ± 4.7	44.6 ± 1.1
PA-240	16.1 ± 2.5	17.3 ± 2.5	43.2 ± 0.4
PA-260	14.8 ± 0.9	12.5 ± 0.9	42.7 ± 0.4
CIL	50.3 ± 3.2	32.4 ± 3.2	72.6 ± 9.4
CIL-180	35.1 ± 3.8	25.0 ± 3.8	68.3 ± 5.1
CIL-200	40.7 ± 0.7	12.6 ± 0.7	74.4 ± 5.1
CIL-220	38.1 ± 1.7	13.4 ± 1.7	78.0 ± 5.5
CIL-240	19.8 ± 2.1	20.7 ± 2.1	77.0 ± 1.0
CIL-260	10.6 ± 3.5	17.7 ± 3.5	64.1 ± 0.9

The values after ± are the standard deviations ($n = 3$).

In contrast, we obtained the opposite result: more cellulose than hemicellulose was decomposed when we wet-torrefied PA and CIL. For example, 39.7 mg of cellulose in CIL with the reduction rate of 78.9% was decomposed when the wet torrefaction temperature reached 260 °C, whereas only 45.4% (14.7 mg) of the hemicellulose was decomposed at 260 °C. It was thus confirmed that the reduction of the solid yield was not due mainly to the decomposition of hemicellulose but rather was due to the decomposition of both cellulose and hemicellulose (Fig. 1). We suspect that the reactivity of both cellulose and hemicellulose in the biomasses was affected by the biomass species and its component weight ratio.

3.3. Elemental analysis of the biomasses and solid fuels

The element content is an important factor in the evaluation of the fuel properties of solid fuels. Higher carbon content and lower oxygen content can efficiently elevate the combustion properties of solid fuel [30]. We thus analyzed the element content of the HL, PA and CIL biomasses and the prepared solid fuels. Table 3 shows that the carbon contents of the three types of solid fuels increased with the increase in the wet torrefaction temperature, whereas the oxygen contents were decreased at higher wet torrefaction temperatures. This phenomenon was due to the reduction of hydroxyl groups in the form of water during wet torrefaction, and the results also indicated that wet torrefaction could largely improve the fuel properties of these biomasses.

The hydrogen and nitrogen contents of the solid fuels showed no significant change compared to their raw biomasses. The element contents of HL-260, PA-260 and CIL-260 reached the same

Table 3
Element contents of biomasses and solid fuels obtained at various temperatures for 10 min.

Sample	C (%)	H (%)	N (%)	O[a] (%)
HL	43.3	6.2	2.5	48.0
HL-180	45.1	5.9	1.3	47.7
HL-200	49.7	6.4	1.9	42.0
HL-220	52.8	6.4	1.9	38.9
HL-240	55.9	6.0	2.2	35.9
HL-260	60.5	6.0	2.7	30.8
PA	44.5	6.1	0.6	48.8
PA-180	51.8	6.5	0.8	40.9
PA-200	56.0	7.0	0.8	36.2
PA-220	57.6	7.0	0.7	34.7
PA-240	59	6.9	0.6	33.5
PA-260	60.7	6.8	0.6	31.9
CIL	46.7	5.6	0.1	47.6
CIL-180	51	5.3	0.4	43.3
CIL-200	53.1	5.2	0.4	41.3
CIL-220	54.7	5	0.4	39.9
CIL-240	57	5.1	0.4	37.5
CIL-260	59.1	4.9	0.3	35.7

[a] Calculated by difference.

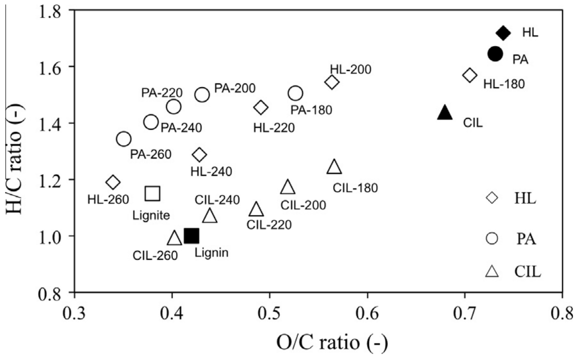

Fig. 2. Van Krevelen diagram of biomasses, solid fuels, lignite as well as lignin.

level as those of lignite with 61.6% carbon, 5.7% hydrogen, and 30.1% oxygen content [16]. The three solid chars obtained in the present study also had similar element contents, although their parent biomasses contained different component weight ratios and their yields at 260 °C were different. We thus speculate that the final element content of the solid fuels may have no relationship to the raw biomass component weight ratio but that this content was related to the original element content of the biomass during wet torrefaction, because the three types of biomass examined herein had similar element contents.

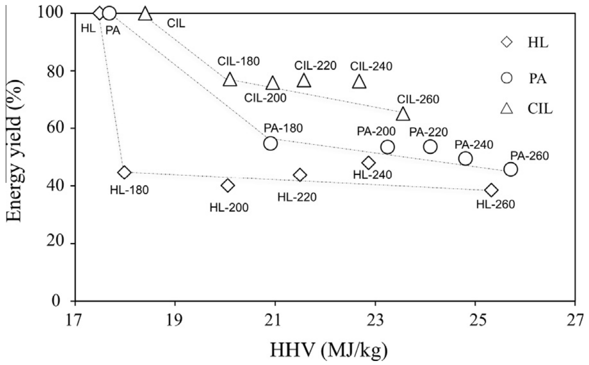

Fig. 4. Energy yield against HHV for all biomasses and their delivered solid fuels.

Variations in the atomic H/C and O/C ratios of solid fuel can be used to efficiently evaluate the fuel grade of solid fuels. We therefore calculated the atomic H/C and O/C ratios from the molecular weight of the raw biomasses and solid fuels (as well as lignin and lignite) and plotted the values obtained in a van Krevelen diagram (Fig. 2). Both the H/C and O/C ratios of all three solid fuels decreased with the increase in the wet torrefaction temperature, and these ratios were much lower than those of their parent biomasses even at 180 °C. The H/C and O/C ratios of HL-260, PA-260 and CIL-260 were close to that of lignite, and the ratios of CIL-260 were also similar to those of lignin. The above results revealed that HL-260, PA-260 and CIL-260 could combust with lignite without a significant change in the combustion properties of lignite. It was reported that a fuel with low H/C and O/C ratios could efficiently reduce energy loss, smoke, and water vapor generation during the combustion process [16]. Therefore, wet torrefaction could largely elevate the combustion properties of a biomass.

The HHV and energy yield of solid fuel are important factors to evaluate the wet torrefaction process and determine the optimum conditions. We examined the HHV calculated from the solid fuel element content and energy yield. The results are shown in Figs. 3 and 4. The HHVs of all three types of solid fuel increased with the increase in the wet torrefaction temperature (Fig. 3), and the energy yield values decreased at the same time (Fig. 4). The increase in HHV was due to the reduction of low-energy chemical bonds such as H–C and O–C and the increase in a high-energy chemical bond (C–C) during wet torrefaction [16].

In the present experiment, the HHVs of HL, PA and CIL were 17.5, 17.7 and 18.4 MJ/kg and they increased to 25.3, 25.7 and 23.6 MJ/kg, respectively, as the temperature increased to 260 °C (Fig. 3a–c). The obtained solid fuels that had HHVs between 23.5 and 25.7 MJ/kg are comparable to those of some commercial coals

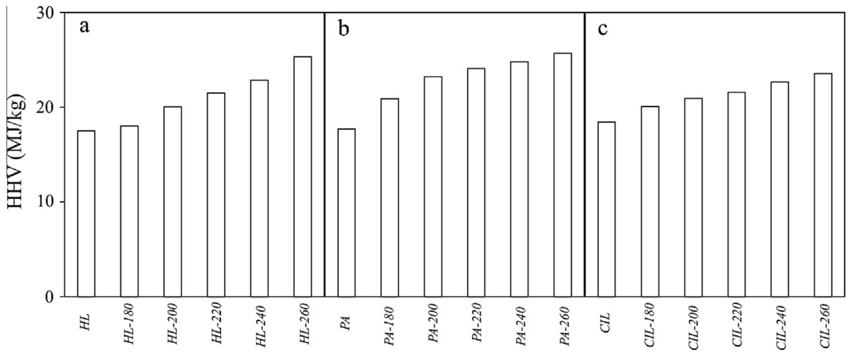

Fig. 3. The HHVs of biomasses and their delivered solid fuels: (a) HL, (b) PA and (c) CIL.

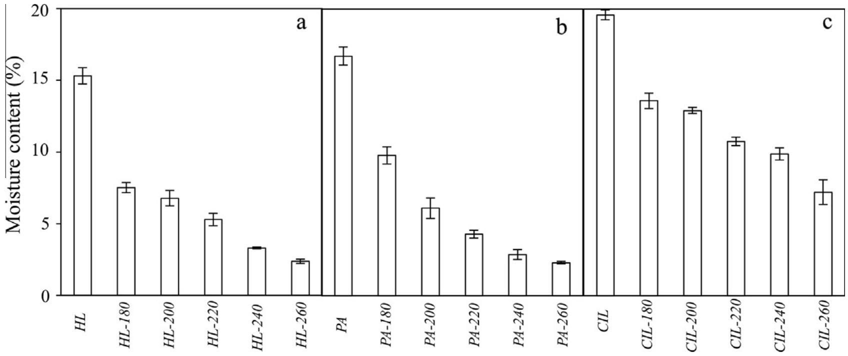

Fig. 5. Moisture content of biomasses and their delivered solid fuels: (a) HL, (b) PA and (c) CIL ($n = 3$).

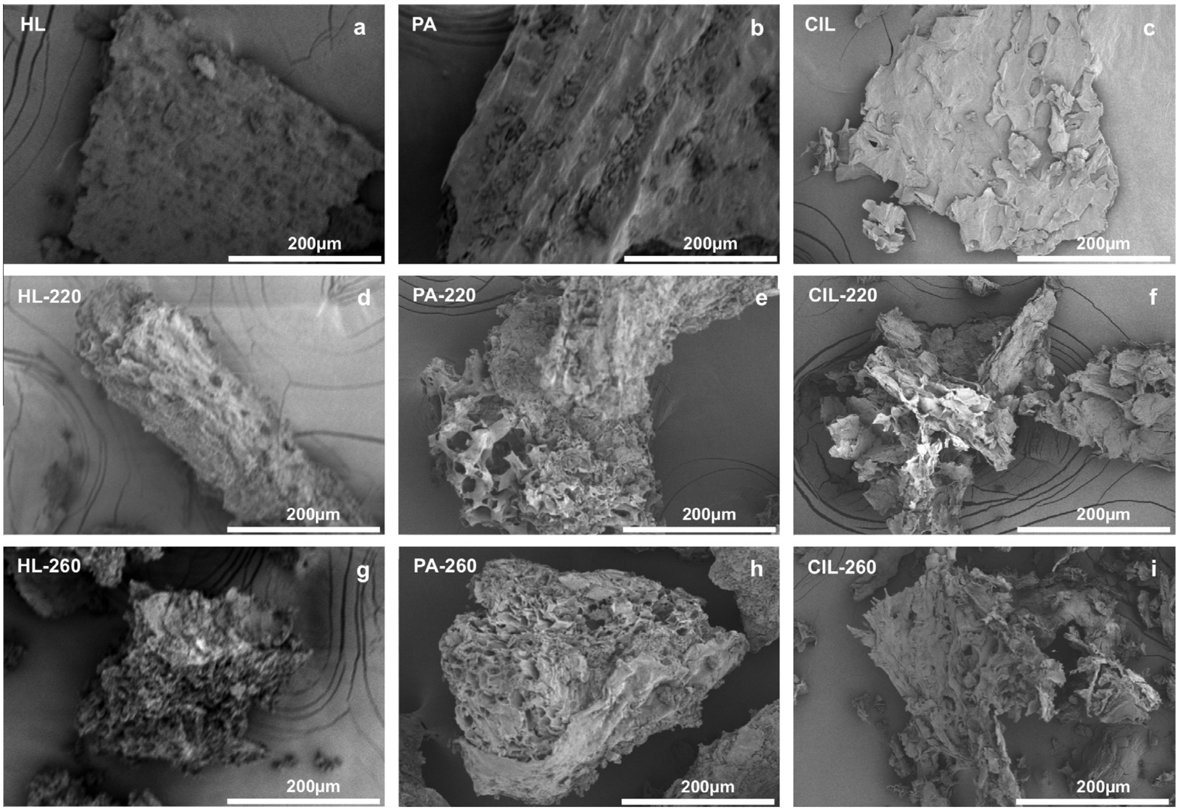

Fig. 6. SEM images of (a) HL, (b) PA, (c) CIL, (d) HL-220, (e) PA-220, (f) CIL-220, (g) HL-260, (h) PA-260 and (i) CIL-260.

such as Northumerland No. 81/2 Sem. Anth. Coal (24.7 MJ/kg), Jhanjra Bonbahal Seam Coal-R-VII (24.1 MJ/kg) and German Braunkohole lignite (25.1 MJ/kg) [31]. Although lignin plays an important role in contributing to the HHV of solid fuel [7], in our study, CIL-260, which has a higher lignin content than those of HL-260 and PA-260 had the lowest HHV. Among these three biomasses, PA-260 had the largest HHV elevation (45.2%) compared to those of HL-260 (44.5%) and CIL-260 (28.3%), although their parent biomasses had similar HHVs. This result was probably due to the differences in biomass components (especially the cellulose and hemicellulose contents) because both of cellulose and hemicellulose were significantly decomposed at higher wet torrefaction temperatures (Table 2). We found that CIL-260 had the lowest HHV and energy content elevation, but it showed a higher energy yield (65.2%) than HL-260 (38.5%) and PA-260 (45.7%) (Fig. 4). This was due to the higher lignin content of CIL, which led to the higher mass yield of solid fuel because the lignin was hardly decomposed at the temperature range from 180 to 260 °C (Table 2). Therefore, the wet torrefaction was able to markedly elevate the HHV of the biomass.

Based on the aforementioned results, we concluded that the solid fuels obtained at a higher wet torrefaction temperature could be co-combusted with German Braunkohole lignite without a significant change in the fuel properties of the German Braunkohole lignite, because of their similar HHVs and H/C and O/C atomic ratios (Fig. 2).

3.4. The hydrophobicity of the biomasses and solid fuels

The hydrophobicity of solid fuel obtained from a biomass is an important factor that is related to the storage and energy density of the solid fuel. A solid fuel with higher hydrophobicity is much more stable and unlikely to deteriorate biologically. We therefore characterized the hydrophobicity of the three types of biomass and solid fuels in this study, evaluated by their final moisture contents after the samples were incubated at 75% relative humidity at 30 °C. As shown in Fig. 5, all of the solid fuels became more hydrophobic with the increase in the wet torrefaction temperature, which was consistent with the result reported by Acharjee et al. [32]. Among these three solid fuels, the solid fuels that from HL and PA were more hydrophobic than that form CIL in the same conditions. For example, HL-260 and PA-260 had the moisture content values of 2.4% and 2.3%, respectively (Fig. 5a and b), which is much lower than that the 7.2% value of CIL-260 (Fig. 5c). Among the three main components of biomass, hemicellulose has a greater water sorption capacity compared to lignin [33] and the process used to obtain the solid fuel affected its hydrophobicity. The differences in hydrophobicity among HL-260, PA-260 and CIL-260 were thus due to the differences in components, because CIL-260 contained a higher content of hemicellulose (19.1%) compared to those of HL-260 (11.9%) and PA-260 (17.9%).

The results described above demonstrate that solid fuel with high hydrophobicity could be obtained through wet torrefaction.

3.5. The SEM topography of the biomasses and solid fuels

Scanning electron microscopy (SEM) is a technique that can detect the surface topography of a sample. We obtained SEM images of the three biomasses and solid fuels to further determine the impact of the wet torrefaction on the biomasses (Fig. 6). The SEM demonstrated that the wet torrefaction had a pronounced impact on all of the solid fuels. We observed that the solid fuels had pore structures and cracks compared to their parent biomasses, and the pore structures and cracks became stronger with the increase in the wet torrefaction temperature (Fig. 6d–i).

The pore structures of CIL-220 and CIL-260 were less pronounced than those of the other two solid fuels obtained under the same conditions, which was probably due to the higher lignin contents of these fuels. This result indicated that the biomass surface was damaged after wet torrefaction, and that this damage was due to the evolution of volatile materials during wet torrefaction, because biochar with higher porosity and various pore structures would be produced by the volatilization of higher volatile materials [34]. As mentioned above, solid fuel contains a high carbon content (Table 3) and it also contains internal pores and cracks. Therefore, the solid fuels obtained in the present study have the potential to be used as carbon feedstock for producing carbon materials such as activated carbon in addition to being used for burning as a bio-fuel.

4. Conclusions

We conducted the wet torrefaction of HL, PA and CIL at various temperatures for 10 min, and we found that the solid fuel from CIL showed the highest yield. The mass loss of biomass after wet torrefaction was due to the significant decomposition of cellulose and hemicellulose. The biomass species and its component weight ratio affected the reactivity of cellulose and hemicellulose. The carbon content of each biomass was largely increased after wet torrefaction. The HHV as well as atomic H/C and O/C ratios were also significantly elevated. The HHVs, H/C and O/C values of HL-260, PA-260 and CIL-260 were similar to those of German Braunkohole lignite, indicating that these solid fuels could be co-combusted with German Braunkohole lignite. CIL-260 had the lowest HHV among the three solid fuels obtained under the same conditions, but it had the highest energy yield. The hydrophobicity of the solid fuel was reduced with the increase in the wet torrefaction temperature. CIL-260 was much more hydrophobic than HL-260 and PA-260 because of its higher hemicellulose content. Pores and cracks were observed on the solid surface and they became stronger at higher temperature. This result indicated that wet torrefaction could completely destroy the biomass surface. We proposed that the obtained solid fuel has the potential to be used as a source of carbon materials such as activated carbon in addition to use as a bio-fuel.

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